

1 **Effects of cultivation and reforestation on suspended**  
2 **sediment concentrations: a case study in a**  
3 **mountainous catchment in China**

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14

## 15 **Abstract**

16 Understanding how sediment concentrations vary with land use/cover is critical for  
17 evaluating the current and future impacts of human activities on river systems. This  
18 paper presents suspended sediment concentration (*SSC*) dynamics and the relationship  
19 between *SSC* and discharge (*Q*) in the 8973-km<sup>2</sup> Du catchment and its sub-catchment  
20 (4635 km<sup>2</sup>). In the Du catchment and its sub-catchment, 4235 and 3980 paired *Q-SSC*  
21 samples, respectively, were collected over 30 years. Under the influence of the  
22 “Household Contract Responsibility System” and Grain-for-Green projects in China,  
23 three periods were designated, the original period (1980s), cultivation period (1990s),  
24 and reforestation period (2000s). The results of a Mann-Kendall test showed that  
25 rainfall slightly increased during the study years; however, the annual discharge and  
26 sediment load significantly decreased. The annual suspended sediment yield of the Du  
27 catchment varied between  $1.3 \times 10^8$  and  $1.0 \times 10^{10}$  kg, and that of the sub-catchment  
28 varied between  $6.3 \times 10^7$  and  $4.3 \times 10^9$  kg s<sup>-1</sup>. The *SSCs* in the catchment and  
29 sub-catchment fluctuated between 1 and 22400 g m<sup>-3</sup> and between 1 and 31800 g m<sup>-3</sup>,  
30 respectively. The mean *SSC* of the Du catchment was relatively stable during the three  
31 periods ( $\pm 83$  g m<sup>-3</sup>). ANOVA indicated that the *SSC* did not significantly change under  
32 cultivation for low and moderate flows, but was significantly different under high  
33 flow during reforestation of the Du catchment. The *SSC* in the sub-catchment was  
34 more variable, and the mean-*SSC* in the sub-catchment varied from  $1058 \pm 2217$  g m<sup>-3</sup>  
35 in the 1980s to  $1256 \pm 2496$  g m<sup>-3</sup> in the 1990s and  $891 \pm 1558$  g m<sup>-3</sup> in the 2000s.  
36 Reforestation significantly decreased the *SSCs* during low and moderate flows,  
37 whereas cultivation increased the *SSCs* during high flow. The sediment rating curves  
38 showed a stable relationship between the *SSC* and *Q* in the Du catchment during the  
39 three periods. However, the *SSC-Q* of the sub-catchment exhibited scattered  
40 relationships during the original and cultivation periods and a more linear relationship  
41 during the reforestation period.

## 42 **1 Introduction**

43 Suspended sediment is conventionally regarded as sediment that is transported by a  
44 fluid and is fine enough to remain suspended in turbulent eddies (Parsons et al., 2015).  
45 Suspended sediment plays important roles in the hydraulics, hydrology, and ecology  
46 of rivers (Luo et al., 2013). Land use/cover is thought to affect hydrology and  
47 suspended sediment yield (*SSY*) (Van Rompaey et al., 2002; Casali et al., 2010).  
48 Although many studies have assumed that forest cover is an effective method for  
49 controlling sediment yield throughout the world (e.g., Mount et al., 2005; Hopmans  
50 and Bren, 2007; Garzía-Ruiz et al., 2008; Stickler et al., 2009; Verbist et al., 2010; Lü  
51 et al., 2015; Wei et al., 2015), other studies have disagreed (e.g., Mizugaki et al., 2008;  
52 Ide et al., 2009). Additionally, many studies have implicated farmland as a major  
53 contributor of sediments (Gafur et al., 2003; Shi et al., 2004; Izaurrealde et al., 2007;  
54 Cerdan et al., 2010). However, whether changes in land use/cover alter soil loss by  
55 changing the runoff volume or by changing the suspended sediment concentration  
56 (*SSC*) has received little attention. The relationships between *SSC* and discharge (*Q*)  
57 have been discussed using sediment rating curves (Walling, 1977), a fuzzy logic  
58 model (Kisi et al., 2006), artificial neural networks (Liu et al., 2012), and other  
59 multivariate regression methods (Francke et al., 2008). *SSCs* are highly variable and  
60 can vary over many orders of magnitude during storm events (Naden and cooper,  
61 1999; Cooper, 2002; Fang et al., 2012). The mean annual/monthly *SSC* fails to capture  
62 the highly episodic nature of sediment transport because >90% of the sediment load  
63 can be transported in <10% of time (Collins et al., 2011). Morehead et al. (2003)  
64 indicated that the suspended sediment load carried by rivers varies spatially and  
65 temporally and that sediment rating curve parameters can exhibit time-dependent  
66 trends. Warrick et al. (2013) concluded that the discharge and sediment relationships  
67 from six coastal rivers varied substantially with time in response to land use. In most  
68 studies, *SSYs* were calculated using *SSCs* and *Q*. However, little work has focused on  
69 the effects of land use/cover change on *SSCs*.

70 China contains 22% of the world's population but only 7% of the world's  
71 croplands (Liu and Diamond, 2005). In China, erosion by water affects an area of  
72  $3.6 \times 10^6 \text{ km}^2$ , or approximately 37% of the country's land area (Ni et al., 2008). Thus,  
73 soil erosion has become an important topic for local and national policy makers. In  
74 the 1980s, a policy called the "Household Contract Responsibility System" was  
75 implemented in China's rural areas. Consequently, more land was reclaimed for  
76 farming. In the late 1990s, the Grain-for-Green project was introduced to increase  
77 forest and grassland cover. To combat soil erosion on sloped croplands, farmland with  
78 slopes  $>25^\circ$  was restored. The farmers who agreed to stop cultivating these lands  
79 received subsidies to cover their losses (Gao et al., 2012). Before this project,  
80 subtropical zones with adequate rainfall were often over-exploited due to economic  
81 and demographic pressures. Cultivation of steeply sloping lands in subtropical areas  
82 can result in serious soil erosion during intense rainfall (Fang et al., 2012). In this  
83 study, a mountainous catchment and its sub-catchment were investigated and analyzed  
84 in detail. This catchment is located in the Danjiangkou Reservoir Area, which is a  
85 source area in the Middle Route Project under the South-to-North Water Transfer  
86 Scheme (the largest water transfer project in the world). The study catchment has  
87 experienced cultivation and reforestation periods. The first part of this study focuses  
88 on how cultivation and reforestation affect  $Q$ ,  $SSC$ , and  $SSY$  at different time scales.  
89 Then, we discuss the dual roles of cultivation and reforestation that affect the  
90 relationship between  $SSC$  and  $Q$ . Finally, the  $SSC$  dynamics in the catchment and  
91 sub-catchment were determined under land use/cover changes.

## 92 **2 Study area and methods**

### 93 **2.1 Study area**

94 This study was conducted in the Du catchment ( $31^\circ30' - 32^\circ37' \text{ N}$ ,  $109^\circ11' - 110^\circ25' \text{ E}$ ),  
95 which is located in Hubei Province, China, and covers an area of  $8973 \text{ km}^2$  (Figure 1).  
96 Elevations within the watershed range from 245 to 3002 m. The sub-catchment

97 (Xinzhou catchment) is located in the northwest region of the Du catchment and  
98 covers an area of 4635 km<sup>2</sup>. The topography in the Du catchment is undulating and is  
99 characterized by mountain ranges, steep slopes and a subtropical climate with a mean  
100 temperature of 15°C. The mean annual precipitation in this region is approximately  
101 1000 mm, with 80% of the precipitation occurring between May and September. The  
102 major soil types include yellow–brown soils, Chao soils, and purple soils (National  
103 Soil Survey Office, 1992), which correspond to Alfisols, Entisols, and Inceptisols,  
104 respectively, according to USDA Soil Taxonomy (Soil Survey Staff, 1999). The major  
105 crops in this region are corn (*Zea mays L.*) and wheat (*Triticum aestivum L.*). There  
106 were 1002 villages with total population of 1.9×10<sup>6</sup> based on the fifth population  
107 census of China in 2000.

108 *Insert: Figure 1*

## 109 **2.2 Land use/cover change**

110 The land cover was digitized as part of a previous research project. Reconnaissance  
111 field surveys were conducted in 2007. A watershed topographic map was used in  
112 combination with 1999 ETM photographs and Landsat imagery from 1987 and 2007.  
113 The land use/cover units were delineated on the photographs and verified in the field.  
114 We assigned the periods of the 1980s, 1990s, and 2000s to original, cultivation, and  
115 reforestation periods, respectively. The areas of the various types of land use/cover are  
116 presented in Tables 1 and 2. In 1987, forestland, farmland, and shrubland covered  
117 areas of 6316 km<sup>2</sup> (70.4%), 919 km<sup>2</sup> (10.2%) and 929 km<sup>2</sup> (10.4%), respectively. The  
118 other land use/cover types covered small areas and included barren land (0.4%),  
119 grassland (7.3%), urban land (0.9%), and water bodies (0.4%) (Table 1). During the  
120 2000s, some steep lands with slopes of more than 25° were converted to forestland.  
121 The area of forestland increased to 75.2% in 2007, whereas the area of farmland  
122 decreased to 6.1% (Figure 2). The sub-catchment experienced a similar change in  
123 farmland, which increased from 11.5% in 1987 to 14.7% in 1999 and decreased to 6.7%  
124 in 2007. However, the change in forestland in the sub-catchment was different from

125 that in the Du catchment, in which forestland increased from 66.3% in 1987 to 67.9%  
126 in 1999 and 74.0% in 2007 (Table 2).

127 *Insert: Figure 2*

128 *Insert: Table 1*

129 *Insert: Table 2*

### 130 **2.3 Data acquisition**

131 All of the hydrological data were obtained from the Hubei Provincial Water  
132 Resources Bureau. Two gauge stations (Zhushan and Xinzhou) and seven weather  
133 stations (nearly evenly distributed) are located in the study catchment. The yearly  
134 average rainfall measured at three weather stations in Xinzhou was very similar to the  
135 mean rainfall measured at the seven weather stations. Therefore, we used the average  
136 annual values of rainfall obtained from the seven stations for the Zhushan and  
137 Xinzhou stations. A continuously recording water-level stage recorder and a silt  
138 sampler (metal type) were used to record discharge and sediment (complemented by  
139 manual samples), respectively. The water stage was measured and transformed into  
140 discharge by using the calibrated rating curve obtained through periodic flow  
141 measurements. *SSCs* were determined using the gravimetric method, in which water  
142 samples were vacuum-filtered through a 0.45- $\mu\text{m}$  filter and the residue was oven-  
143 dried at 105°C for 24 h. The weight of each dried residue and the initial sample  
144 volume were used to obtain the *SSC* ( $\text{g m}^{-3}$ ). Next, the *SSY* was calculated from the  
145 *SSC* and *Q*. During a month, the total *SSY* was the sum *SSY* of each event. Monthly  
146 *SSC* was calculated by monthly *SSY* and *Q*. During rainfall events, the sampling  
147 measurement frequency was increased several times each day. Paired *SSC-Q* data  
148 were obtained during rainfall-runoff events. Because bed load measurements were not  
149 performed in this area, this study does not consider bed load sediment transport. From  
150 1980 to 2009, 4235 paired *SSC-Q* samples were collected at the Zhushan station and  
151 3980 samples were collected at the Xinzhou station. This study uses several variables,

152 and their meanings and abbreviations are shown in Table 3. To distinguish between  
 153 the variables of the two gauges, we used  $Qd$ ,  $Dd$ ,  $SSYd$ , and  $SSCd$  for the Zhushan  
 154 station (Du catchment) and  $Qx$ ,  $Dx$ ,  $SSYx$ , and  $SSCx$  for the Xinzhou station  
 155 (sub-catchment).

156 *Insert: Table 3*

157 The variables for  $D$ ,  $SSY_i$  and  $SSY$  are calculated as follows:

$$158 \quad D = Q/A \quad (1)$$

$$159 \quad SSY_i = SSC_i \times Q_i \quad (2)$$

$$160 \quad SSY = \int_1^n SSY_i \quad (3)$$

161 where  $A$  is the area of the catchment and  $SSY_i$ ,  $SSC_i$  and  $Q_i$  are the suspended sediment  
 162 yield, suspended sediment concentration, and discharge during period  $i$ , respectively.

## 163 **2.4 Statistical analyses**

164 The Mann-Kendall test, which was proposed by Mann (1945) and Kendall (1975),  
 165 was used to identify trends in  $P$ ,  $Q$  and  $SSY$  during the 30-year study period. The  $S$   
 166 statistic was calculated as follows:

$$167 \quad S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad (4)$$

168 where  $n$  is the number of data points,  $x_i$  and  $x_j$  are the respective data values in the  
 169 time series  $i$  and  $j$  ( $j > 1$ ), and  $\text{sgn}(x_j - x_i)$  is the sign function (Gao et al., 2012), which is  
 170 determined as follows:

$$171 \quad \text{sgn}(x_j - x_i) = \begin{cases} +1, & \text{if } x_j - x_i > 0 \\ 0, & \text{if } x_j - x_i = 0 \\ -1, & \text{if } x_j - x_i < 0 \end{cases} \quad (5)$$

172 The variance is computed as

$$173 \quad \text{VAR}(S) = \frac{1}{18} \left[ n(n-1)(2n+5) - \sum_{i=1}^q t_i(t_i-1)(2t_i+5) \right] \quad (6)$$

174 where  $n$  is the number of data points,  $q$  is the number of tied groups and  $t_i$  is the  
 175 number of data values in the  $i$ th group. The standard test statistic,  $Z$ , is computed as  
 176 follows:

$$177 \quad Z = \begin{cases} \frac{S-1}{\sqrt{\text{VAR}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{VAR}(S)}} & \text{if } S < 0 \end{cases} \quad (7)$$

178 A positive value of  $Z$  indicates an upward trend, and a negative value of  $Z$   
 179 indicates a downward trend. We use the threshold of  $\pm 1.96$  for significant difference  
 180 (Gao et al., 2012). The Mann-Kendall statistical test has frequently been used to  
 181 quantify the significance of trends in hydro-meteorological time series (Gocic and  
 182 Trajkovic, 2013).

183 To discuss relationships between  $SSC$  and  $Q$ , hydrologists often use sediment  
 184 rating curves. The most common approach is to fit a power curve to the normal data  
 185 (Khanchoul et al., 2010) as follows:

$$186 \quad SSC = \alpha Q^\beta \quad (8)$$

187 Here,  $\alpha$  and  $\beta$  are constants in the non-linear regression equation. The non-linear  
 188 model assumes that the dependent variable ( $SSC$ ) has a constant variance (scatter),  
 189 which typically does not occur because the scatter around the regression generally  
 190 increases with increasing  $Q$  (Harrington and Harrington, 2013). The Mann-Kendall  
 191 test was performed in MATLAB 7.0.



## 192 **3 Results**

### 193 **3.1 Stream flow and sediment yield during different periods**

194 Figure 3 shows the annual  $P$ ,  $D$  and  $SSY$  for the hydrological years of 1980-2009  
195 from the Zhushan and Xinzhou gauges. The annual  $P$  fluctuated between 665 and  
196 1219 mm. The annual  $Dd$  and  $Dx$  varied between 253 to 873 mm and 279 to 931 mm,  
197 respectively. The annual  $SSY$  varied between  $1.3 \times 10^8$  and  $1.0 \times 10^{10}$  kg yr<sup>-1</sup> from the  
198 Zhushan gauge and between  $6.3 \times 10^7$  and  $4.3 \times 10^9$  kg yr<sup>-1</sup> from the Xinzhou gauge. To  
199 identify the relationships between the annual  $P$ ,  $Dd$ ,  $Dx$ ,  $SSYd$ , and  $SSYx$ , we generated  
200 a Pearson's correlation matrix, as shown in Figure 4. The analysis showed significant  
201 correlations between all of the variables ( $n=30$ ,  $p<0.0001$ ). During the low-flow years  
202 (e.g., 1997 or 2001),  $SSYd$  was similar to  $SSYx$ . However, during the high-flow years  
203 (e.g., 1983 or 2005),  $SSYd$  was several times greater than  $SSYx$ .

204 *Insert: Figures 3 and 4*

205 The Mann-Kendall test was applied to the annual  $P$ ,  $D$  and  $SSY$  data for  
206 1980-2009. The test shows a decreasing but not significant trend for  $P$ , a significant (5%  
207 level) decreasing trend for  $Qd$ , and highly significant decreasing trends for  $Qx$ ,  $SSYx$   
208 and  $SSYd$  (1% level) (Figure 5). After 2000,  $P$  shows an increasing trend and  $Q$  and  
209  $SSY$  show decreasing trends.

210 *Insert: Figure 5*

211 To better understand the dynamics of  $Q$  and  $SSC$ , Tables 4 and 5 compare the  
212 observed average monthly  $Q$  and  $SSC$  among the three periods monitored at the  
213 Zhushan and Xinzhou gauges.

214 *Insert: Tables 4 and 5*

215 During 1980s-1990s, the annual  $Qd$  showed a decreasing trend (Table 4), with  
216 only 3 of 12 months showing a slightly increasing trend. The rate of decrease varied  
217 from -3.3% to -53.0%. In addition,  $Qx$  exhibited a decreasing trend that was similar to

218 that of  $Q_d$  during the same period. During 1990s-2000s,  $Q_d$  greatly increased from 1%  
219 to 34% during 9 of 12 months. Meanwhile,  $Q_x$  increased over eight months and  
220 fluctuated between 10% and 42%. During 1990s-2000s,  $Q_d$  and  $Q_x$  both exhibited a  
221 more obvious increasing trend during the winter than during the flow seasons.

222 Table 5 shows the monthly mean  $SSC$  from the two gauges.  $SSC_d$  decreased (-1%  
223 to -66%) during the flow seasons (May to September), except in August, when it  
224 slightly increased (2%) during 1980s-1990s. The decrease of  $SSC_d$  did not coincide  
225 with that of  $Q_d$ . During 1990s-2000s, the decrease in  $SSC_d$  was more obvious than  
226 that in 1980s-1990s. Eight of ten months experienced a decreasing change, and the  
227 change over seven months was  $>-40\%$ . In addition, the  $SSC_x$  decreased over six  
228 months and increased during the other four months during 1980s-1990s. During  
229 1990s-2000s, the  $SSC_x$  decreased over seven months, and four out of five months  
230 showed a decreasing trend during the flow season. However, the monthly  $SSC$  is  
231 calculated by  $SSY$  and  $Q$  and is not the actual  $SSC$ . To better understand  $SSC$   
232 dynamics, paired  $SSC$ - $Q$  data collected by monitoring should be discussed.

### 233 3.2 $SSC$ - $Q$ dynamics

234 Figure 6 shows the statistical characteristics of the  $SSC$  and  $Q$  during the three  
235 periods. The mean- $SSC_d$  was relatively stable during the three periods ( $\pm 83 \text{ g m}^{-3}$ ),  
236 and the mean- $SSC_x$  varied from  $1058 \text{ g m}^{-3}$  in the 1980s to  $1256 \text{ g m}^{-3}$  in the 1990s  
237 and then decreased to  $891 \text{ g m}^{-3}$  in the 2000s. In the 1980s, the max  $SSC_d$  and max  
238  $SSC_x$  were 22400 and  $31800 \text{ g m}^{-3}$ , respectively. Next, the max  $SSC_d$  shape decreased  
239 to  $20000 \text{ g m}^{-3}$  during the 1990s and to  $17800 \text{ g m}^{-3}$  during the 2000s. Meanwhile, the  
240 max  $SSC_x$  decreased to 26900 and  $19200 \text{ g m}^{-3}$  during the 1990s and 2000s,  
241 respectively. The max  $Q_x$  was more variable than the max  $Q_d$  and was  $12400 \text{ g m}^{-3}$  in  
242 the 1980s,  $3610 \text{ g m}^{-3}$  in the 1990s and  $3010 \text{ g m}^{-3}$  in the 2000s. However, the rate of  
243 change of the mean  $Q_x$  was similar to that of the mean  $Q_d$ .

244 *Insert: Figure 6*

245 Figure 7 shows that the *SSCs* varied by several orders of magnitude for a given  
246 discharge at both gauges. *SSCd* and *SSCx* fluctuated between 1 and 22400 g m<sup>-3</sup> and  
247 between 1 and 31800 g m<sup>-3</sup>, respectively. The maximum *SSCx* (31800 g m<sup>-3</sup>) was  
248 larger than the maximum *SSCd* (21400 g m<sup>-3</sup>). In Figure 7, *SSCd-Qd* maintained a  
249 stable relationship during the three periods (1980s, 1990s, and 2000s). However,  
250 *SSCx-Qx* showed a scattered relationship from 1980s and 1990s and showed a more  
251 linear relationship from 2000s. During the three periods, the max *Qd* decreased from  
252 9880 to 6140 and 5070 m<sup>3</sup> s<sup>-1</sup>, respectively. Meanwhile, the max *Qx* was reduced  
253 from 5960 to 3580 and 2990 m<sup>3</sup> s<sup>-1</sup>, respectively.

254 *Insert: Figure 7*

255 The relationship between *SSC* and *Q* is complicated. To better understand the  
256 dynamics of *SSC*, *SSC* was sorted by ranking the paired *Q* values, which were  
257 classified using a threshold level approach (e.g., low flow ( $Q \leq 25\%$ ), moderate flow  
258 ( $25 < Q < 75\%$ ), and high flow ( $Q \geq 75\%$ ). The *SSC* dynamics were compared under  
259 different flow regimes. For the sub-catchment, the thresholds were 188 and 674 m<sup>3</sup> s<sup>-1</sup>  
260 for the minimum 25% and maximum 25%, respectively. For *Qd*, the thresholds of the  
261 minimum and maximum 25% were 332 and 1100 m<sup>3</sup> s<sup>-1</sup>, respectively. Figure 8  
262 presents box plots for *SSCd* and *SSCx* during the three periods for the three flow  
263 grades. The box plots indicate the maximum, 75%, 50%, 25%, and minimum values  
264 for each *SSC* (outliers are excluded). For the sub-catchment, *SSCx* increased between  
265 the original period and the cultivation period for moderate and high flow, but not for  
266 low flow. Then, *SSCx* decreased during the reforestation period for all flows. At the  
267 Zhushan station, *SSCd* was larger during the cultivation period for both moderate and  
268 high flows. During the reforestation period, the *SSCd* during low flow was higher than  
269 during the other periods.

270 *Insert: Figure 8*

271 Six ANOVA tests were performed using *SSC* as the dependent variable and using  
272 the different periods (land use) as independent variables. ANOVA was only conducted  
273 for the same flow during different periods. One-way ANOVA (Table 6) revealed that

274 *SSC<sub>x</sub>* showed significant differences among the different periods for all three types of  
275 flows ( $p < 0.001$ ). However, a significant difference in *SSC<sub>d</sub>* was only observed among  
276 high flows ( $p < 0.001$ ). No statistically significant differences were observed among  
277 the *SSC<sub>d</sub>* values during the different periods for low or moderate flows.

278 *Insert: Table 6*

## 279 **4 Discussion**

280 Land use/cover has been widely documented to have dire environmental  
281 consequences through their adverse impacts on soil and water qualities (Zhang et al.,  
282 2015). Olang et al (2011) indicated that 40% and 51 of forest and agriculture land  
283 respectively revealed reduced runoff volumes by about 12%, while 86% land cover of  
284 agriculture increased runoff volumes by about 12 %. Buendia (2015) et al studied the  
285 effects of afforestation on runoff at a Pyrenean Basin (2807 km<sup>2</sup>), the results show  
286 with forest of sub-basins increase ranging between 19% and 57% account for ~40%  
287 of the observed decrease in annual runoff. Liu et al (2014) demonstrated that  
288 afforestation leads to increased runoff in dry seasons in Yarlung Zangbo River basin.  
289 In this study, land use/cover changes significantly affect *Q* and *SSY* (Tables 4 and 5).  
290 During the cultivation period, an increase in farmland resulted in an obvious  
291 decreasing trend in *Q* in the Du catchment and its sub-catchment. The sediment  
292 concentration in the direct runoff from a slope consists of a combination of the  
293 sediment stored on the slope and that generated by flow erosion during the current  
294 rainfall event (Aksoy and Kavvas 2005; Rankinen et al., 2010). Large storms generate  
295 sufficient surface runoff to deliver sediment from the uplands to the stream. In forest  
296 catchments over flow typically occurs only in a small fraction of the catchment, it is  
297 most likely to occur very close to the stream (Underwood et al., 2015). Reforestation  
298 many increased the return period of peak flow and peak sediment yield (Keesstra,  
299 2007). Borrelli et al (2013) illustrated that a disturbed forest sector could produce  
300 about 74% more net erosion than a nine times larger, undisturbed forest sector. High

301 *SSCs* are not detected in the absence of a high flow velocity to carry the suspended  
302 sediment to the outlet of a catchment. *SSCs* are determined by onsite sediment  
303 production and the connectivity of sediment sources to the channel. Sediment  
304 delivered to the channel can deposited (Keesstra et al., 2009). When runoff is  
305 decreased, its erodibility is reduced (Bakker et al., 2008; Van Rompaey et al., 2002).  
306 Reduced stream flow can reduce the sediment transport capacity and increase the  
307 probability for further sediment deposition in the river (Zhu et al., 2015).  
308 Human-induced modifications of land use/cover in river basins may cause strong  
309 geomorphic responses by disturbing sediment supply, transport and deposition  
310 processes (Liebault et al., 2005).

311 Hydrological studies rely on the analysis of processes at different spatial scales  
312 (García-Ruiz et al., 2008). Sediment yield and watershed areas have been elucidated  
313 in many studies (e.g., Renschler and Harbor, 2002; de Vente and Poesen, 2005). The  
314 mean-*SSC* was stable during the study years in the Du catchment, and the mean-*SSC*  
315 varied in the sub-catchment. The increase in  $Q_x$  was larger than the increase in  $Q_d$ .  
316 The monitored sub-catchment covered approximately half of the entire catchment.  
317 Likewise, the combined mean annual discharge volume of the sub-catchment was  
318 nearly half of the total catchment output (i.e., a deficit of approximately 50% at the  
319 outlet). However, the *SSC* dynamics were more variable. Due to sediment delivery  
320 problems, sediment is generated on catchment slopes and is either stored on the  
321 surface or removed (Rankinen et al, 2010). Only a fraction of the gross soil erosion  
322 within a catchment will reach the outlet and be represented in the sediment yield. In  
323 addition, stream flow erodes the sediment directly from the surface or causes channel  
324 erosion, which both removes the stored surface layer of detached sediment.

325 Our previous study in Du catchment showed that the area scale dominates the  
326 sediment delivery ratio (Shi et al., 2014). The sediment stored in the gullies is flushed  
327 to the river when a certain threshold is exceeded, and the deposition of sediment in  
328 channels is flushed at higher discharges. The max *SSC<sub>x</sub>* is greater than the max *SSC<sub>d</sub>*  
329 (31800 vs. 22400 g m<sup>-3</sup>). One possible explanation is the sediment stock is depleted

330 during a flood, this process not occur simultaneously within the entire river basin and  
331 results in gradually decreasing *SSCs* downstream (Doomen et al., 2008). Cultivation  
332 or reforestation alter the slope surfaces but do not remove gullies and channels. The  
333 *SSCs* in Zhushan were only significantly different during high flow and the  
334 reforestation period when the forest cover greatly increased.

## 335 **5 Conclusions**

336 This study investigated  $Q$  and *SSC* dynamics for 30 years under cultivation and  
337 reforestation. The results of a Mann-Kendall test showed that rainfall slightly  
338 increased during the study years; however, the annual discharge and sediment load  
339 significantly decreased. The sediment flux is extremely spatially and temporally  
340 variable. The relationship between *SSC* and  $Q$  is complicated. Reforestation caused  
341 significant differences in the *SSC* for both low and moderate flows. For low and  
342 moderate flow, the changes in *SSY* primarily resulted from runoff, while the *SSC*  
343 showed little change. For the sub-catchment, the changes in the *SSC* were more  
344 sensitive to land use/cover changes. Meanwhile, cultivation resulted in significant  
345 differences in the *SSC* for high flow. Overall, our results provide useful information  
346 regarding *SSC* dynamics relative to land use/cover changes in mountainous  
347 catchments in a subtropical climate, which have largely been undocumented in the  
348 literature.

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Table 1 Land use/cover type and change ratio during 1978-2007 in the Du catchment

Land use/cover	Land use/cover (km <sup>2</sup> ) and ratio			Land use/cover change (km <sup>2</sup> ) and change ratio		
	1987	1999	2007	1999-1987	2007-1999	2007-1987
Water	35 (0.4%)	26 (0.3%)	31 (0.4%)	-9 (-0.1%)	5 (0.1%)	-4 (-0.0%)
Urban land	81 (0.9%)	88 (1.0%)	115 (1.3%)	8 (0.1%)	26 (0.3%)	34 (0.4%)
Barren land	37 (0.4%)	38 (0.4%)	62 (0.7%)	1 (0.0%)	24 (0.3%)	26 (0.3%)
Forest	6316 (70.4%)	6232 (69.5%)	6841 (75.2%)	-84 (-0.9%)	609 (6.8%)	525 (5.9%)
Shrub	929 (10.4%)	846 (9.4%)	851 (9.9%)	-83 (-0.9%)	5 (0.1%)	-78 (-0.9%)
Grass	657 (7.3%)	525 (5.8%)	551 (6.4%)	-132 (-1.5%)	26 (0.3%)	-106 (-1.2%)
Farmland	919 (10.2%)	1218 (13.6%)	522 (6.1%)	299 (3.3%)	-695 (-7.7%)	-397 (-4.4%)

Table 2 Land use/cover and change ratio during 1978-2007 in the Xinzhou catchment

Land use/cover	Land use/cover (km <sup>2</sup> ) and ratio			Land use/cover change (km <sup>2</sup> )		
	1987	1999	2007	1999-1987	2007-1999	2007-1987
Water	16 (0.3%)	15 (0.3%)	14 (0.3%)	-1 (0.0%)	-1 (0.0%)	-2 (0.0%)
Urban land	52 (1.1%)	57 (1.2%)	51 (1.1%)	5 (0.1%)	-6 (-0.1%)	-1 (0.0%)
Barren land	20 (0.4%)	22 (0.5%)	41 (0.9%)	2 (0.0%)	19 (0.4%)	21(0.5%)
Forest	3072 (66.3%)	3148 (67.9%)	3432 (74.0%)	76 (1.6%)	284 (6.1%)	360 (7.8%)
Shrub	537 (11.6%)	422 (9.1%)	479 (10.3%)	-115 (-2.5%)	57 (1.2%)	-58 (-1.3%)
Grass	404 (8.7%)	290 (6.3%)	307 (6.6%)	-114 (-2.5%)	17 (0.4%)	-97 (-2.1%)
Farmland	534 (11.5%)	679 (14.7%)	312 (6.7%)	145 (3.1%)	-367 (-7.9%)	-222 (-4.8%)

532

Table 3 Variables and associated abbreviations used in the statistical analysis

Abbreviations	Variables	Units
<i>P</i>	Rainfall	mm
<i>Q</i>	Stream flow	m <sup>3</sup> s <sup>-1</sup>
<i>D</i>	Discharge depth	mm
<i>SSY</i>	Suspended sediment yield	kg or g s <sup>-1</sup>
<i>SSC</i>	Suspended sediment concentration	kg m <sup>-3</sup> or g m <sup>-3</sup>

533

Table 4 Monthly mean stream flow from the Xinzhou and Zhushan gauges

	$Q_d$ ( $m^3 s^{-1}$ )			Change (100%)		$Q_x$ ( $m^3 s^{-1}$ )			Change (100%)	
	1980s	1990s	2000s	C1	C 2	1980s	1990s	2000s	C1	C 2
Jan	35	33	41	-5.7%	24.2%	17	13	19	-23.5%	46.2%
Feb	37	46	49	24.3%	6.5%	18	19	21	5.6%	10.5%
Mar	85	96	74	12.9%	-22.9%	42	46	31	9.5%	-32.6%
Apr	186	146	160	-21.5%	9.6%	92	72	61	-21.7%	-15.3%
May	185	200	203	8.1%	1.5%	89	97	89	9.0%	-8.2%
Jun	274	224	192	-18.2%	-14.3%	132	115	111	-12.9%	-3.5%
Jul	412	223	262	-45.9%	17.5%	207	119	173	-42.5%	45.4%
Aug	269	260	257	-3.3%	-1.2%	129	136	156	5.4%	14.7%
Sep	338	159	202	-53.0%	27.0%	173	76	109	-56.1%	43.4%
Oct	255	136	155	-46.7%	14.0%	123	67	103	-45.5%	53.7%
Dec	121	94	95	-22.3%	1.1%	57	42	47	-26.3%	11.9%
Nov	49	41	62	-16.3%	51.2%	23	18	30	-21.7%	66.7%
Average	187	138	146	-26.2%	5.8%	92	68	79	-26.1%	16.2%

534 Note: C1 is the change for 1990-1980; C2 is the change for 2000-1990

535



Table 5 Monthly mean suspended sediment concentration from the Xinzhou and Zhushan gauges

	SSCd (g m <sup>-3</sup> )			Change (100%)		SSCx (g m <sup>-3</sup> )			Change (100%)	
	1980s	1990s	2000s	C1	C2	1980s	1990s	2000s	C1	C2
Jan	0	0	0	-	-	0	0	0	-	-
Feb	10	1	2	-90%	100%	3	0	0	-100%	-
Mar	7	15	1	114%	-93%	3	12	1	300%	-92%
Apr	224	147	56	-34%	-62%	118	81	28	-31%	-65%
May	427	256	139	-40%	-46%	298	128	127	-57%	-1%
Jun	629	623	321	-1%	-48%	471	718	430	52%	-40%
Jul	1222	755	686	-38%	-9%	929	895	603	-4%	-33%
Aug	942	963	364	2%	-62%	736	961	411	31%	-57%
Sep	674	229	239	-66%	4%	409	115	186	-72%	62%
Oct	268	146	46	-46%	-68%	185	84	84	-55%	0%
Dec	26	86	1	231%	-99%	18	54	1	200%	-98%
Nov	0	0	0	-	-	0	0	0	-	-
Average	369	268	155	-27.4%	-42.1%	264	254	156	-3.8%	-38.6%

536 Note: C1 is the change for 1990s-1980s; C2 is the change for 2000s-1990s.

Suspended sediment primarily loads during the flow season. Rainfall is rare in the winter (Dec, Nov and Jan), and the stream flow is dominated by a base flow; thus, in most years, there is no suspended sediment load.

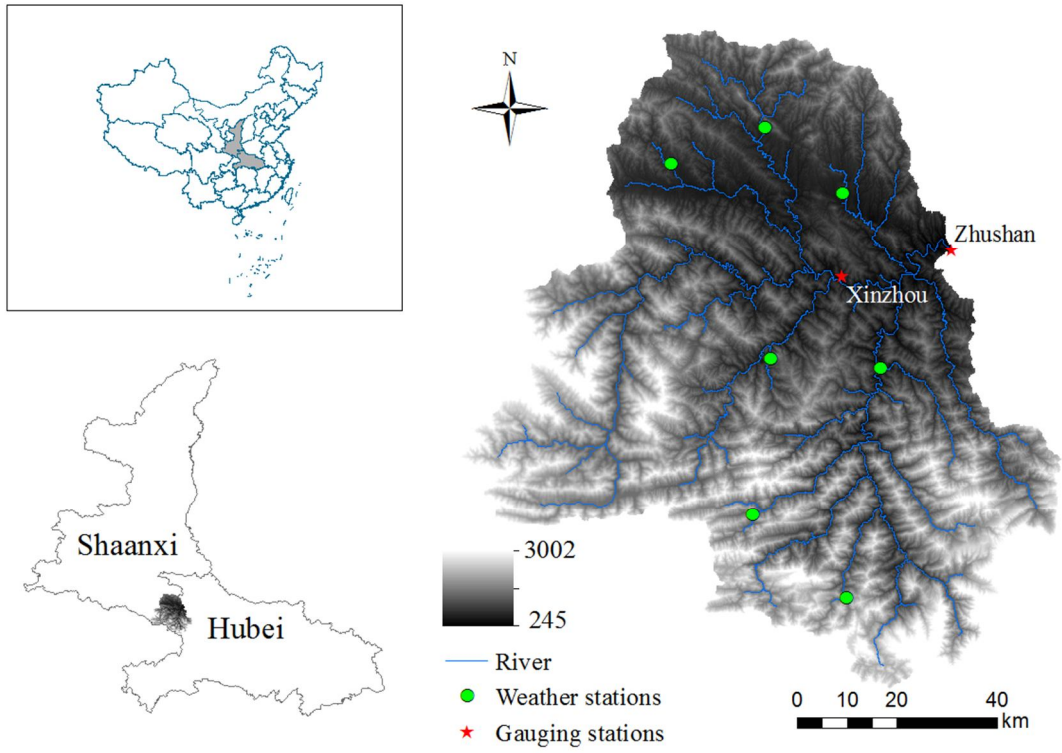
537

Table 6 Mean *SSC* values and one-way ANOVA of *SSCs* during the different periods

		Original	Cultivation	Reforestation	p value
Mean <i>SSCd</i> (g m <sup>-3</sup> )	Low flow	0.49	0.50	0.44	0.285
	Moderate flow	0.83	0.86	0.97	0.080
	High flow	2.42	2.43	2.02*	0.002
Mean <i>SSCx</i> (g m <sup>-3</sup> )	Low flow	0.68	0.66	0.36*	0.000
	Moderate flow	0.87	0.97	0.64*	0.000
	High flow	1.80	2.83*	1.80	0.000

Note: ANOVA was only conducted for the same flow during different periods; \* means significant difference at  $\alpha=0.05$

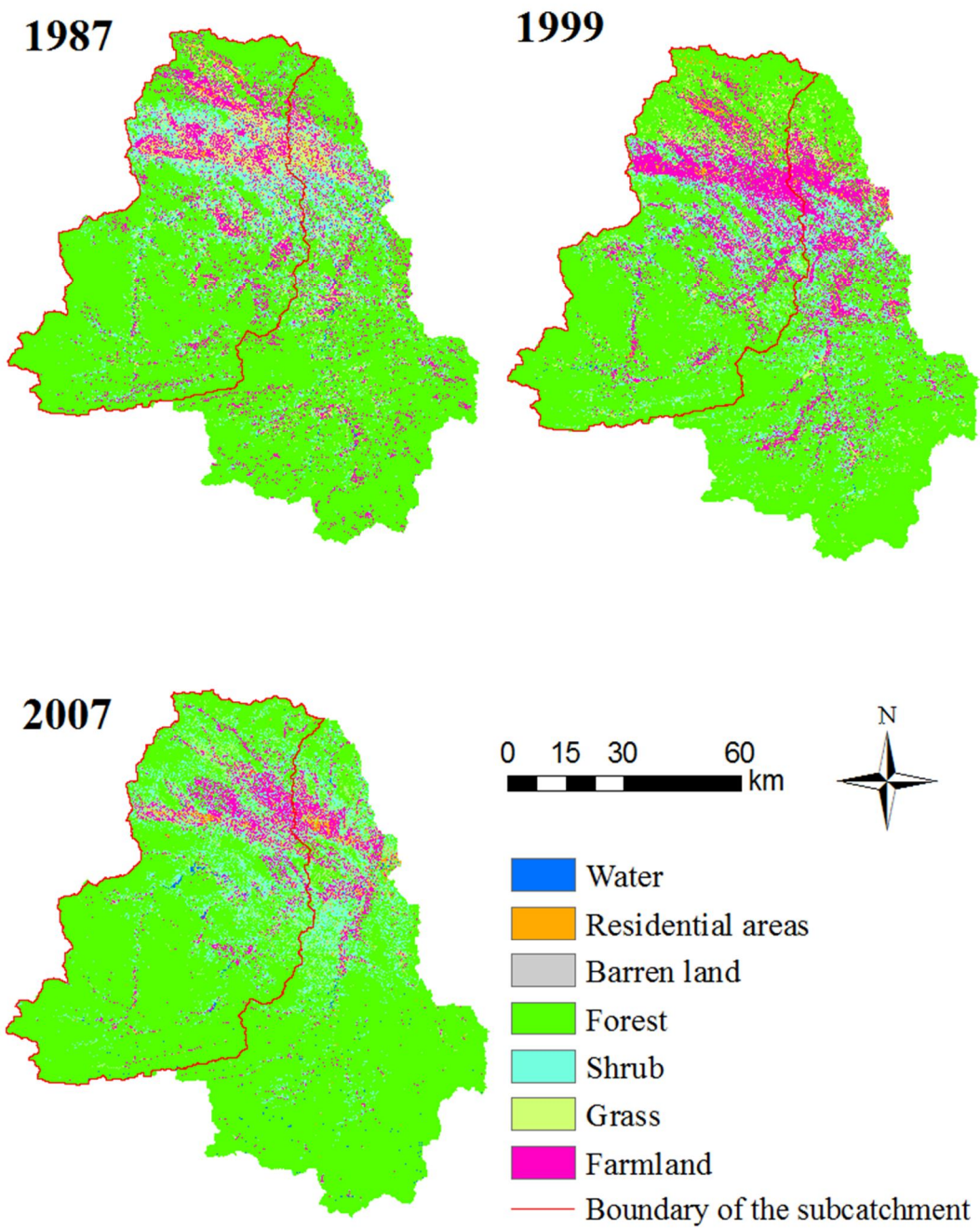
- 538 Figure captions:
- 539 Figure 1 Location of study area
- 540 Figure 2 Land use changes during the three periods
- 541 Figure 3 Annual P, D and SSY for the hydrological years of 1980-2009 from the Zhushan and Xinzhou
- 542 gauges
- 543 Figure 4 Bivariate scatter-plot matrix of selected variables
- 544 Figure 5 Results of the Mann-Kendall test
- 545 Figure 6 Descriptive statistics of Q and SSC
- 546 Figure 7 SSC-Q relationships during the three periods for the two gauges
- 547 Figure 8 Box plots of SSC
- 548



549

550 Figure 1

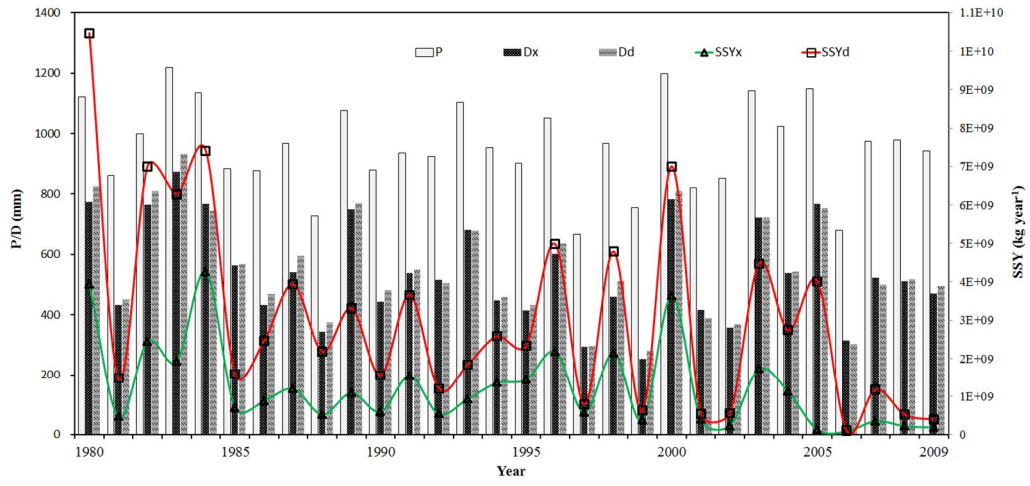
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553 Figure 2

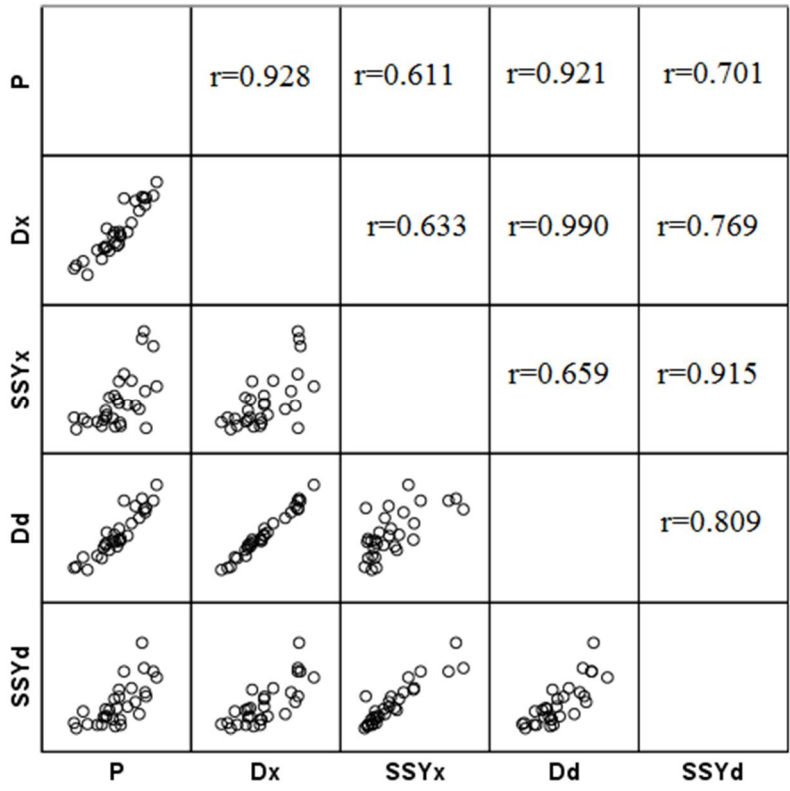
554



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556 Figure 3

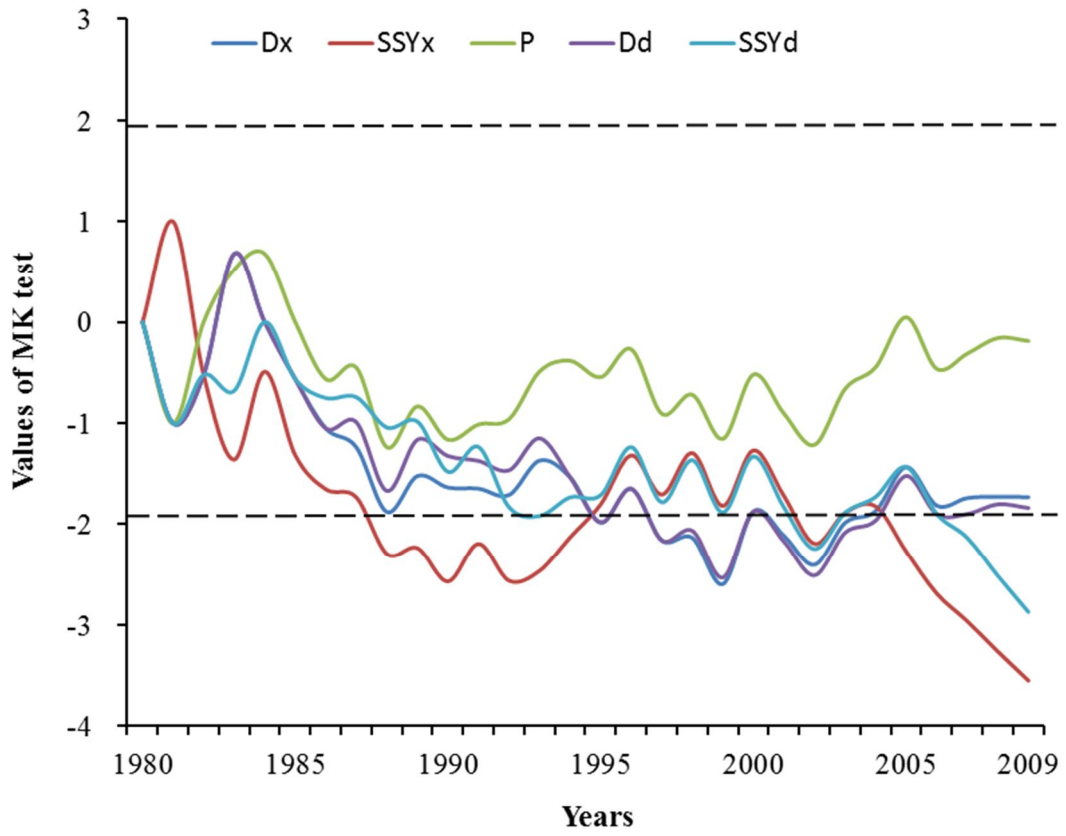
557



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559 Figure 4

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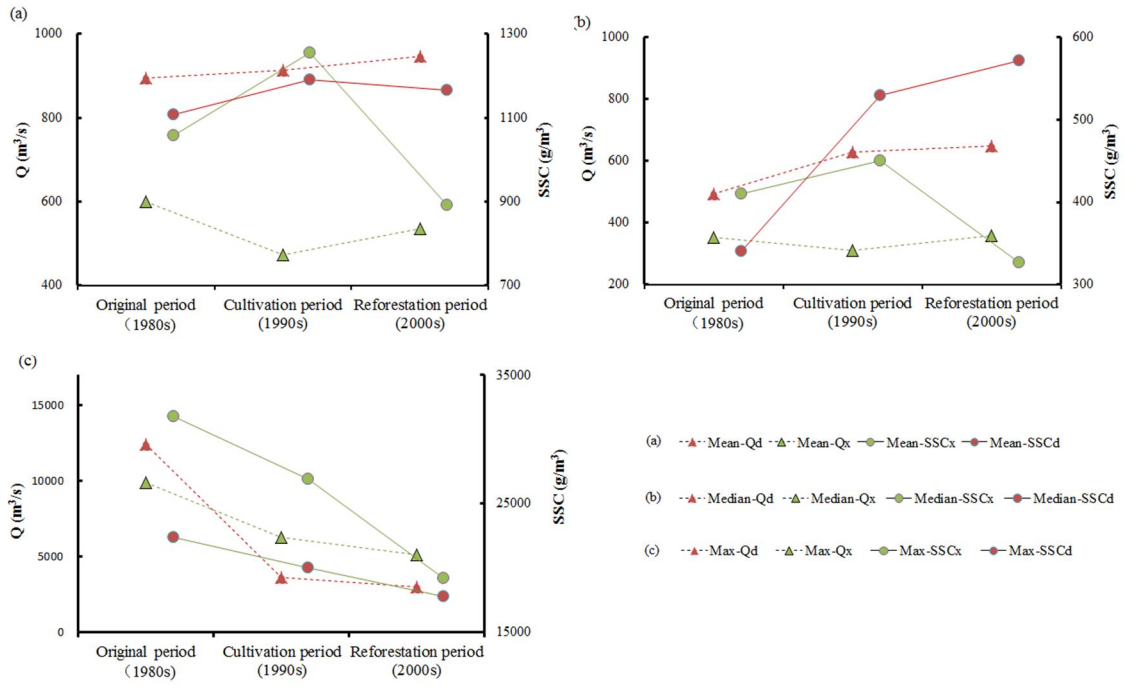


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562 Figure 5

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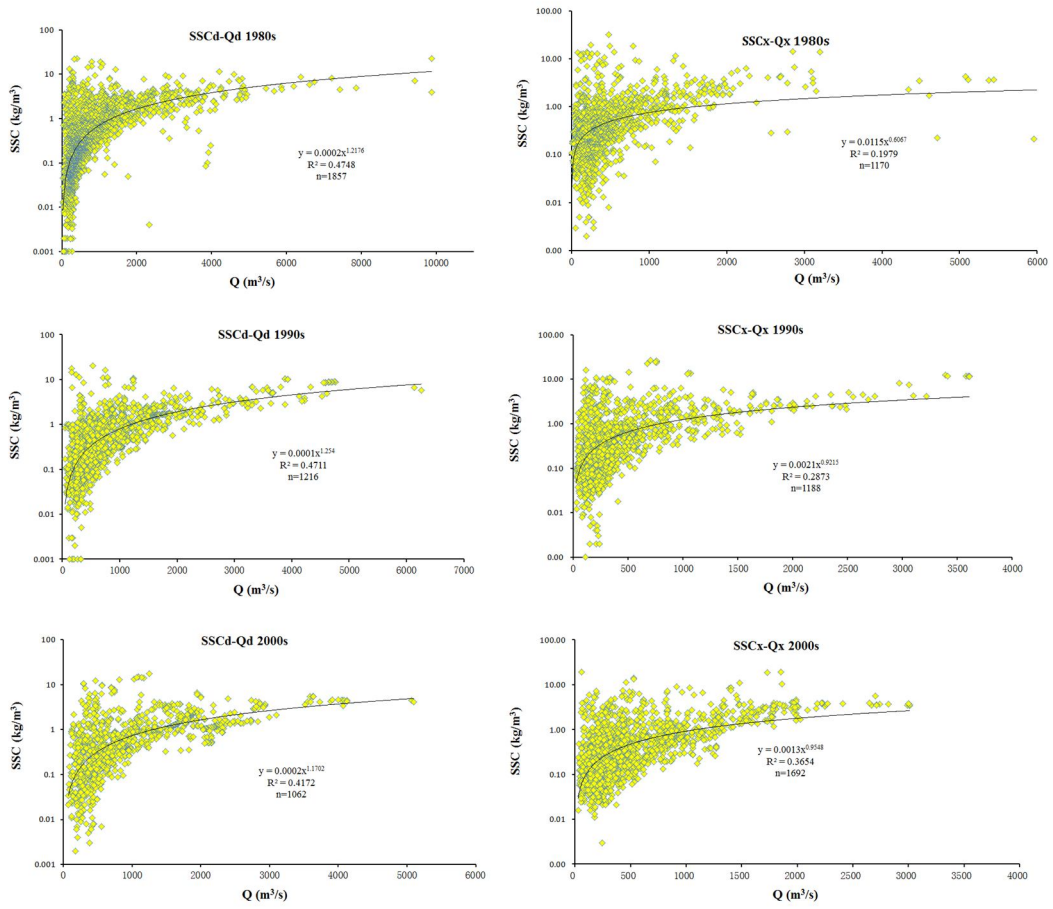




564

565 Figure 6

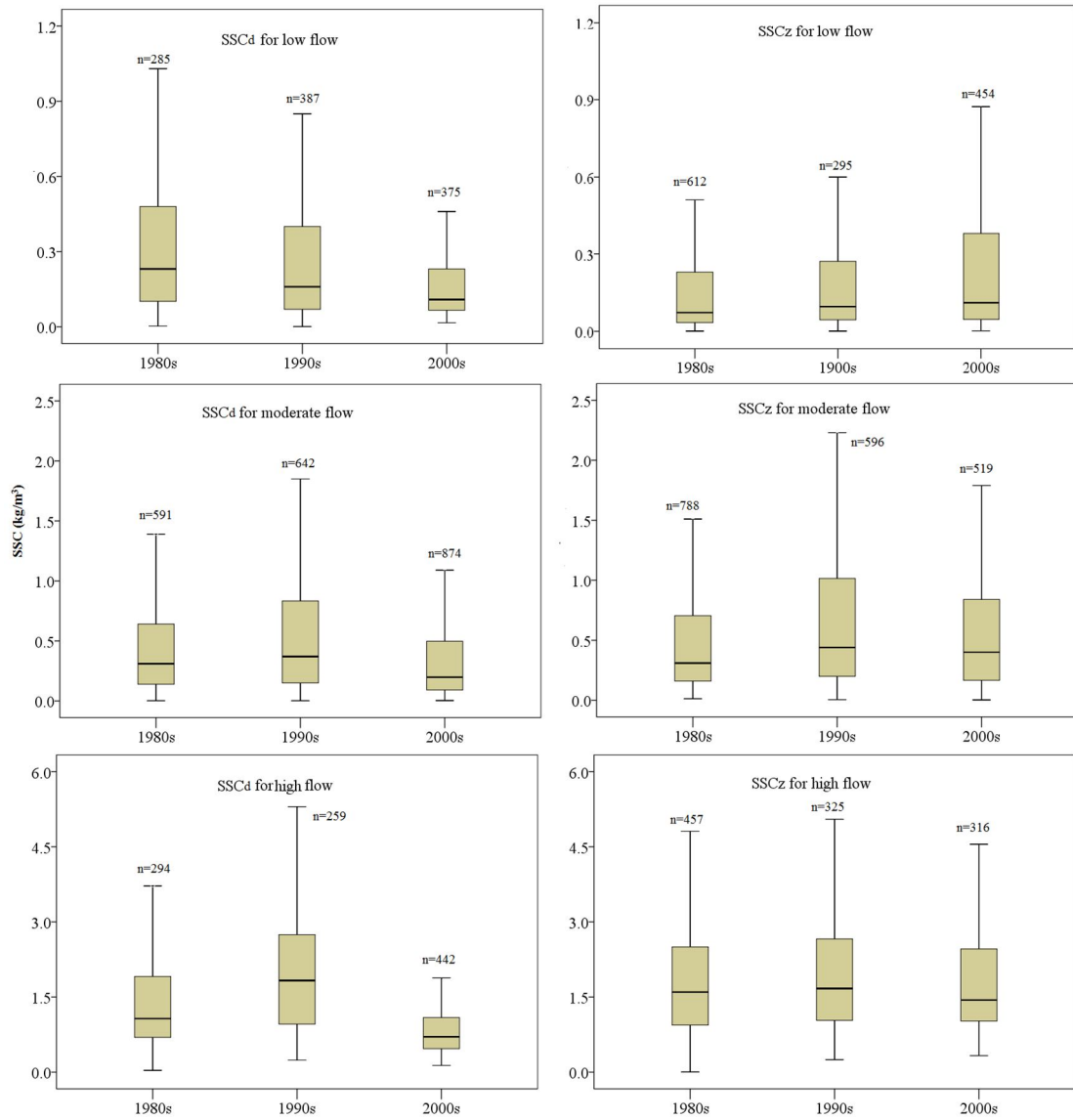
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568 Figure 7

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572 Figure 8